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Characteristics of Phase-Correcting Fresnel Zone Plates and Elliptical Waveguides

FINAL REPORT

by
James C. Wiltse

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Atlanta, GA 30332

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13. ABSTRACT *(Maximum 200 words)*
The primary area of activity has been concentrated on the investigations relating to Fresnel zone plate antennas. A secondary effort has dealt with the characteristics of propagation in waveguides of elliptical cross section. In both cases, applications at microwave and millimeter-wavelengths have been emphasized. Thorough literature searches were conducted, and the results are given in Appendices A and B. The zone plate work has dealt with both transmission and reflection types, and has included considering the off-axis-fed cases. In the latter case, the plate may consist of elliptical zones, rather than the usual circular configuration. In general, the characteristics studied include far-field patterns, focal region fields, off-axis performance, bandwidth, and aberrations. In the case of Propagation in elliptical waveguides, the attenuation and modal properties were studied for enclosed metal waveguides, coaxial transmission lines, and various surface waveguides. Contributions to these investigations were made by Dr. Glenn Smith and Dr. Helen C. Wiltse and Messrs. C.A.Barrett, J.E. Garrett, T.H. Gfroerer, and K. Demino.

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Statement of Problems Studied

The primary area of activity has been concentrated on the investigations relating to Fresnel zone plate antennas. A secondary effort has dealt with the characteristics of propagation in waveguides of elliptical cross section. In both cases, applications at microwave and millimeter-wavelengths have been emphasized.

The zone plate work has dealt with both transmission and reflection types, and has included considering the off-axis-fed cases. In the latter case, the plate may consist of elliptical zones, rather than the usual circular configuration. In general, the characteristics studied include far-field patterns, focal region fields, off-axis performance, bandwidth, and aberrations.

In the case of propagation in elliptical waveguides, the attenuation and modal properties were studied for enclosed metal waveguides, coaxial transmission lines, and various surface waveguides.

Summary of Most Important Results

Most of the specific results are given in the attached publications and bibliographies (Appendices A, B, and C). Results were obtained analytically, experimentally (measurements at 35 GHz), and by thorough searches of the literature. Several conference presentations were given, the most recent one being a paper entitled "Millimeter-Wave Fresnel Zone Plate Antennas" given at the SPIE International Conference on Millimeter and Submillimeter Waves and Applications, San Diego, California, January 10, 1994. The manuscript for that talk is in preparation and copies will be available in the near future. Typical results are summarized for such parameters as beamwidth, peak and average sidelobe levels, gain, focal characteristics, off-axis performance, scan capability, field of view, secondary foci, frequency dependence, and aberrations. An important result of the investigation was the discovery of a major error in an earlier paper (highly-regarded and apparently thorough) by Sanyal and Singh (Appendix A, reference 1968B). Another valuable result, obtained from the literature search, was the uncovering of several articles in the Indian and Russian literature concerning curved zone plates (i.e., spherical and paraboloidal shapes). Compared with planar zone plates, they have sharper focal regions and wider fields of view.

The literature searches for both the Fresnel zone plate and elliptical examples were quite comprehensive, as may be seen from Appendices A and B. These also include alphabetical author indexes.

List of Publications

The publications listed below are attached as Appendix C:

1. J. C. Wiltse, "Fresnel Zone Plate Antennas for Microwaves and Millimeter Waves," Proc. of the Workshop on Millimeter-Wave Power Generation and Beam Control, Huntsville, AL, Sept. 14-16, 1993.

2. J. C. Wiltse and C. A. Barrett, "Off-axis Fresnel Zone Plate Antenna," SPIE/Seventeenth International Conference on Infrared and Millimeter Waves, Pasadena, CA, vol. 1929, pp. 280-281, Dec. 14-17, 1992.

3. C. A. Barrett and J. C. Wiltse, "Design Parameters for Zone Plate Antennas," 1992 IEEE AP/S International Symposium," pp. 608-611, July, 1992.

4. J. C. Wiltse, "Recent Developments in Fresnel Zone Plate Antennas at Millimeter Wavelengths," 16th Int'l Conf. on Infrared and Millimeter Waves, Lausanne, Switzerland, SPIE Vol. 1576, pp. 497-498, August, 1991.

5. J. C. Wiltse and T. H. Gfroerer, "Further Comments on Modes of Elliptical Waveguides," IEEE Trans. on Microwave Theory and Techniques, Vol. 40, p. 175, Jan. 1992.

6. J. C. Wiltse and T. H. Gfroerer, "Errors in Solutions for Waveguides of Elliptical Cross-Section," Digest of the 16th International Conference on Infrared and Millimeter Waves, Lausanne, Switzerland, SPIE Vol. 1576, pp. 600-601, August 1991.

List of Scientific Personnel

The principal investigator was Dr. James Wiltse. The program concentrated on supporting several graduate research assistants, listed below:

C. A. Barrett

James E. Garrett (Ph.D. student - Electrical Engineering)

T. H. Gfroerer

K. Demino (Ph.D. student- Physics)

Messrs. Barrett, Garrett, and Gfroerer received their master's degrees at Georgia Tech while involved in this research.

Appendices

Appendix A - FRESNEL ZONE PLATE ANTENNAS

Appendix B - ELLIPTICAL WAVEGUIDES AND TRANSMISSION LINES

Appendix C - COPIES OF PUBLISHED PAPERS

APPENDIX A

FRESNEL ZONE PLATE ANTENNAS

BIBLIOGRAPHY AND ALPHABETICAL AUTHOR INDEX

J.E. GARRETT, J.C. WILTSE
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APPENDIX B

ELLIPTICAL WAVEGUIDES AND TRANSMISSION LINES

BIBLIOGRAPHY AND ALPHABETICAL AUTHOR INDEX

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ELLIPTICAL WAVEGUIDES AND TRANSMISSION LINES

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Abstract

This report contains a compilation of papers and an author index dealing with guided-wave propagation in transmission lines and waveguides having elliptical cross sections. This includes enclosed waveguides (with or without internal dielectric or ferrite media), coaxial transmission lines, and various surface waveguides, with some references to elliptical optical fibers. Except for a few notable early items, the great majority (about 130) of the references cover the period from 1959 to 1992. The main emphasis is on microwave and millimeter-wave examples, although several typical fiber-optics cases are cited. A few references are included because of their general tutorial nature.

INTRODUCTION

In recent years scores of papers have been published dealing with enclosed or surface waveguides of elliptical cross section. Examples have included hollow metal waveguide, enclosed waveguide filled with one or more dielectrics, coaxial transmission lines, stripline, dielectric surface waveguides (rod, tape, or tube), and variations for wave guides employing anisotropic media. Some of these types have been investigated experimentally as well as theoretically, and several have been used in practical microwave-frequency applications, such as in feed lines for antenna installations. Elliptical waveguides offer various advantages, such as providing lower attenuation for a given waveguide cross-sectional area and/or wider bandwidth for single-mode operation, being physically more flexible than circular or rectangular guide, preserving the field polarization orientation with waveguide length, and in some cases having reduced tolerances or a quasi-planar structure (e.g., ellipse with high eccentricity).

This bibliography starts with a seminal paper by L. J. Chu in 1938 (dealing with propagation in hollow metal waveguides) and covers the period up to March, 1993. The list is grouped by types of waveguides (e.g., hollow metal waveguides, surface waveguides, etc.) and is given in chronological order within these types. The last category consists of general references, mostly dealing with Mathieu functions, although the original paper by E. Mathieu, dated 1868 (concerning vibrations of an elliptical membrane) is also included. Almost all of the items deal with guided waves, but not scattering of electromagnetic waves. The emphasis is on microwave or millimeter-wave examples, although enough papers dealing with fiber optics are given to illustrate the applications in the optical field. Limiting the number of fiber optics articles was felt to be necessary because a very large number have been published. In the other waveguide categories, almost all of the available papers are listed. The largest grouping is for surface waveguides (about 50 entries), with the second-largest group being hollow metal waveguides.

The first four sections of the bibliography are quite complete, containing most papers on the relevant subject matter. Exceptions include two papers which were excluded because they contain errors. Section V, "Dielectric or Dielectric-Coated Surface Waveguides", includes most of the microwave or millimeter papers, but only selected articles on fiber optics. Those included contained information that was relevant to general elliptical waveguide theory. Many of the more recent titles from this category (1989 and later) deal specifically with topics relevant to fiber optical signal transmission and are outside the scope of this bibliography. Two papers (#108 and #126) while not specifically addressing topics pertinent to the bibliography, contained sections that were tutorial in nature. These articles provide background information about the mathematics of elliptical geometries that the newcomer to the field may find useful. Following the bibliography is an alphabetical list of all authors, cross-indexed to their articles in the bibliography.

To obtain the various titles contained in this bibliography, a detailed literary search was performed. Data bases that were searched included INSPec, ENGIneering, CARLuncover, NTIS (technical reports), and MATHSCI on DIALOG information services. The INSPec and ENGIneering databases were readily available to the authors via the Georgia Institute of Technology electronic library system, while the remaining databases were consulted by library personnel. Ultimately, a thorough search of all of the above mentioned databases was performed by a library professional to insure that all relevant titles were obtained. Even this limited search located a very large number of journals. The reference lists of papers obtained in this way were scanned to locate additional titles. The authors hope that this compilation will be useful and time-saving for workers in the field.

ELLIPTICAL WAVEGUIDES AND TRANSMISSION LINES

BIBLIOGRAPHY AND ALPHABETICAL AUTHOR INDEX

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APPENDIX C

Copies of Published Papers

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Workshop on

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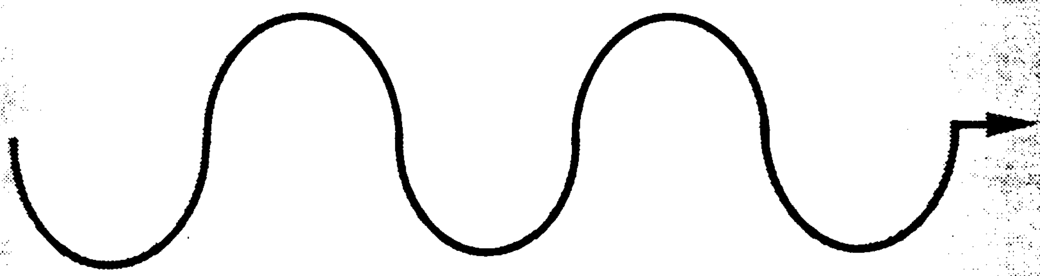


September 14-16, 1993
University of Alabama in Huntsville
Material Science Building
Huntsville, Alabama

Fresnel Zone Plate Antennas for Microwaves and Millimeter Waves

James C. Wiltse
Georgia Tech Research Institute
Atlanta, Georgia 30332

ABSTRACT

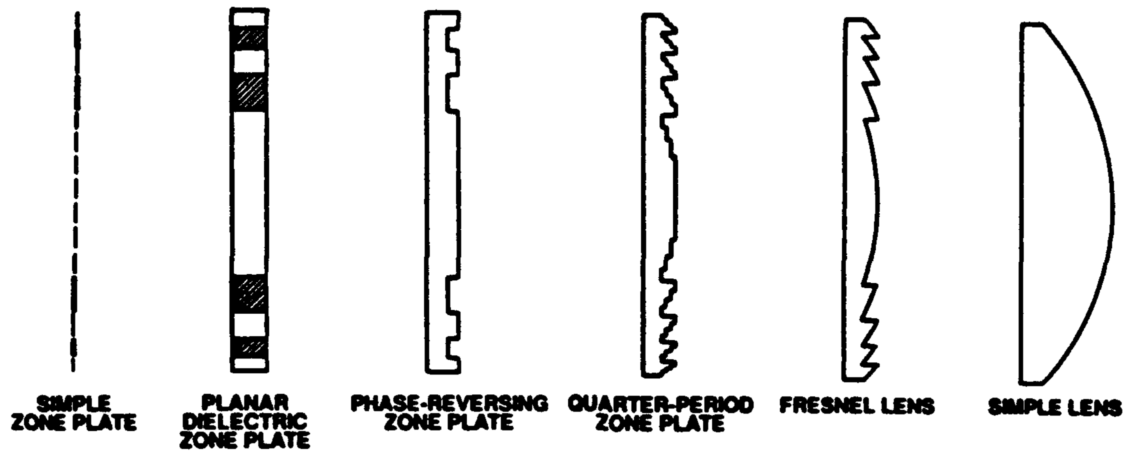
The performance characteristics of phase-correcting Fresnel zone plate antennas have been investigated at microwave and millimeter wavelengths. Both transmission-type (i.e., lens-like) and reflection type antennas have been analyzed, fabricated, and tested. Parameters such as far-field patterns, efficiency, focal region properties, and off-axis performance have been considered. Measurements were made at 35 GHz, and results are also available for frequencies from 11 GHz to W-band.

Zone plates may be used with off-axis feeds. For angles up to about 20° off-set, the performance is well-behaved, with minor degradation. The design is given for a transmission type and an equivalent reflecting version having a 17° feed offset. An investigation has been carried out for angles larger than 20°, and the results indicate that the annular zones on the plate should not be circular. A ray-tracing analysis shows that they need to be non-confocal ellipses, and these results will be described. The analysis has been completed for both transmission or reflection-type zone plates. The results give information on the maximum field-of-view and on the number of feeds that may be utilized, and on the scan capability. Some discussion of non-planar(e.g., spherical or paraboloidal) zone plates will also be given.

INTRODUCTION

Fresnel zone plates provide performance comparable to, or in some cases, better than lenses or parabolic reflector antennas and have been used in transmission or in reflector configurations [1,2]. In general, Fresnel zone plates may be lower in cost, simpler, lighter in weight, have lower loss and wider fields of view, while still providing the same beamwidth and comparable sidelobe performance to that obtainable from a lens or paraboloid reflector of equal aperture. There are two basic types, the partially opaque (in which alternate zones are blocked) and the phase-correcting (in which all zones are utilized). Figure 1 shows some examples. The partially opaque type only uses about half of the available aperture and is very inefficient. Nonetheless, it is sometimes employed at microwave frequencies because it is so easy to build, and is often used at optical frequencies because of the difficulty of introducing phase correcting zones with dimensions of the order of the wavelength. In the optical range, very long focal lengths are often used (e.g., 600 times the plate diameter), whereas at millimeter and microwave frequencies the focal lengths and diameters are often comparable in size. Also, optical zone plates may have large numbers of annular zones (perhaps 200 to 300), while at millimeter wavelengths there may be only a few zones (e.g., 5 to 30). This is illustrated in Figures 2 - 4. The number of zones increases with diameter (D) for a fixed focal length (F), with shorter focal lengths for a fixed diameter, and with smaller F/D [3].

Figure 1. RELATION BETWEEN LENSES AND ZONE PLATE



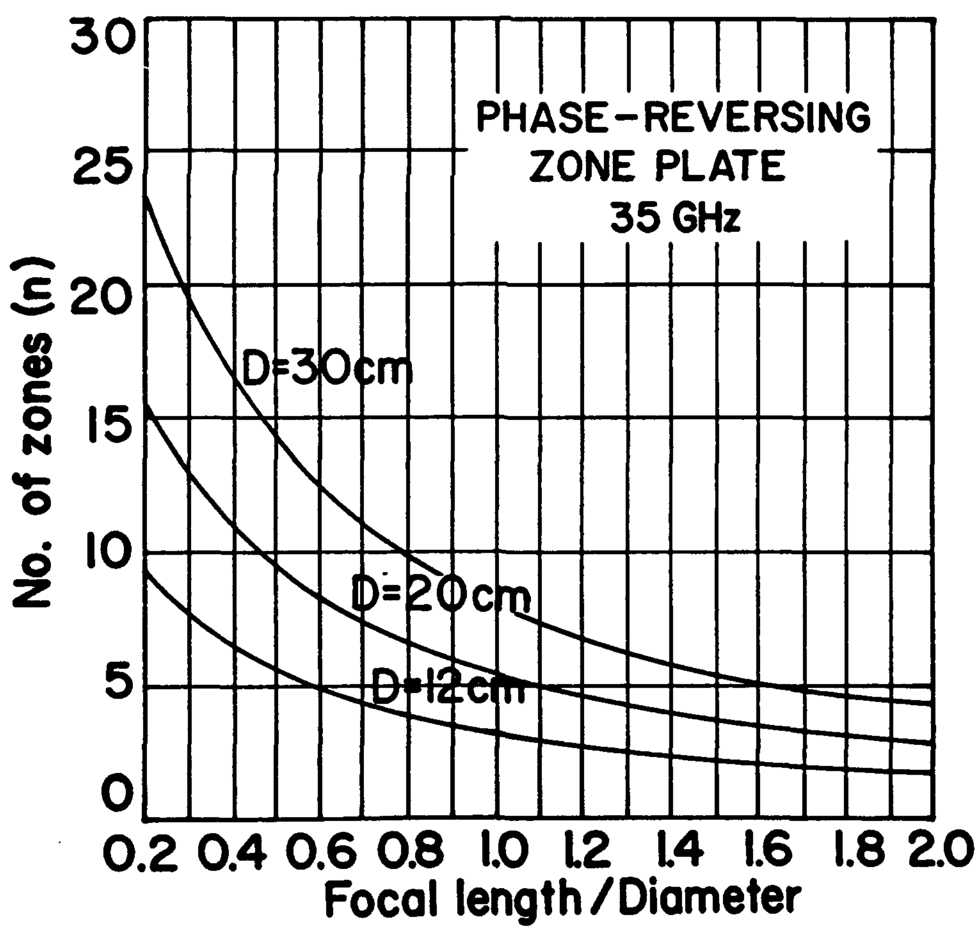


Figure 2. Number of zones as a function of focal length over diameter.

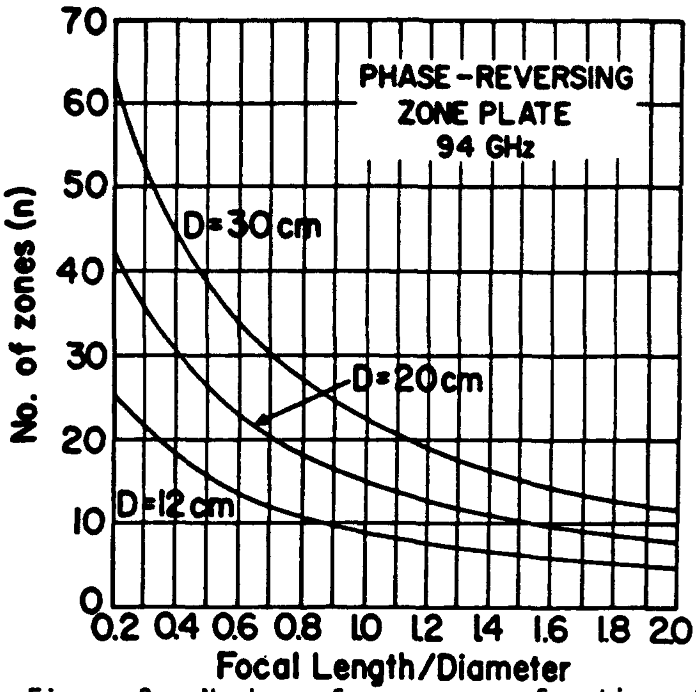


Figure 3. Number of zones as a function of focal length over diameter at 94 GHz.

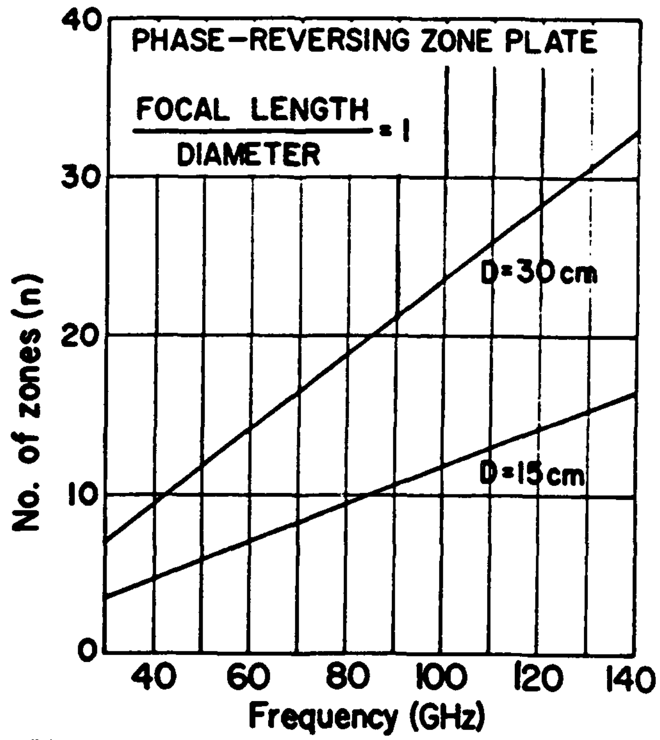


Figure 4. Number of zones as a function of frequency for two diameters.

BACKGROUND AND HISTORY

Some of the background has been summarized in References 1 and 2. Phase-correcting zone plates have been used at millimeter wavelengths for three decades [4]. In that time scores of papers have been published, but many of these deal with optical applications or with the partially-opaque zone plates, and therefore may not be of interest to the millimeter-wave or microwave user. Even those that deal with these latter cases are sometimes narrow in scope, limited in range of parameters, and frequently do not reference other relevant work.

Nonetheless the literature contains references to phase-correcting zone plates that have been designed and tested at various microwave frequencies, as well as K_a-band, 90 GHz, 140 GHz, 210 and 235 GHz (see Table I). Some of these have employed better than half-wave phase correction, such as quarter-wave correction. In these investigations a number of technical requirements and needs have been addressed. They include far-field patterns (beamwidth, peak sidelobe level, average sidelobe level), gain, bandwidth and frequency dependence, aberrations, knowledge of the focal region fields, off-axis performance, field of view, and efficiency or effectiveness when compared with a lens. In spite of a significant amount of this prior work, there is no unified collection of results, but examples will be discussed below.

Far field patterns have been measured and/or calculated by several groups [1,4,5-10], and in general the patterns are similar to those from a lens having a comparable aperture distribution. That is, beamwidths are approximately the same, as are principal sidelobe levels. Secondary sidelobes are typically 20 to 30 dB below the main beam. Attempts have been made to find a simple, closed-form expression for the far-field pattern, but normally one must perform a computer-numerical solution for the Kirchoff integral [7]. Gain is somewhat less than for a lens, but this depends upon the number of phase steps utilized, and this is analyzed in Reference 9, which also shows that far-out sidelobes are 35 to 45 dB below the main beam (see also references 1 and 10).

The bandwidth and frequency dependence are related to the focal length over diameter (F/D) and the number of zones [1, 11], but percentage bandwidths of 12% to 20% are typical. The main effect is the change in the axial location of the focal point. A large number of investigations have dealt with the knowledge of the fields in the vicinity of the focal region [11-16]. Obviously, the zone plate does not focus energy to a "point", but produces a diffraction pattern (similar to that of a lens), with a prominent main beam surrounded by sidelobes and second-order foci. It is important to know the structure of these fields in a detailed, quantitative manner. Understanding this structure gives information about off-axis performance and aberrations.

A very comprehensive investigation in this area was conducted by Sanyal and Singh [13]. They measured the fields in the axial and transverse directions around the focal area and did it for a range of frequencies (8.2 to 10.4 GHz) for both a semi-opaque simple zone plate and a phase-correcting example. However, it was discovered by the present author that their results are flawed because the design of the phase-correcting plate was in error. The more recent references [14-16] have provided further information about the focal region fields, but it is still an area that needs further quantitative theoretical and measured results.

Most zone plates are planar, and, in fact, this is often touted as an advantage (i.e., simple construction,, less weight and volume, lower cost, and usefulness in a microelectronics planar environment). Nonetheless, there have been several investigations of spherical and paraboidal plates. An extensive series of papers was published by authors in India [16-21], but because they were published in Indian journals, most researchers have been unaware of them and they have seldom been referenced by

American or European authors. (The Indian authors similarly did not reference the relevant Western publications). These and other references [22-23] have given quantitative information about the characteristics of curved zone plates, which offer advantages such as a better axial focusing property, wider field of view, and aerodynamic shapes.

35 GHz DESIGNS

As a part of the present program, quarter-wave phase correcting zone plates have been designed for, and tested at, 35 GHz. One design, shown in Figure 5, is for a transmission-type zone plate, and the measured far-field pattern is shown in Figure 6. The second (Figure 7) is the design for a reflecting antenna (an aluminum mirror was placed on the right side or back of the plate). The antenna pattern for the reflector case when fed at an angle of 17 degrees is given in Figure 8. The feed is at -34 degrees. Other measured results will be presented at the Workshop.

SUMMARY

Although a large amount of research has been conducted on Fresnel zone plate antennas, there is no unified summary of the theory or experimental results. Nonetheless, it is well-established that these antennas provide excellent performance. A bibliography of important references has been assembled and will be made available to interested parties.

ACKNOWLEDGEMENT

The author would like to acknowledge the assistance of Dr. Glenn Smith and Mr. James E. Garrett. This work was supported by the U.S. Army Research Office. Opinions, interpretations, conclusions and recommendations are those of the author and not necessarily endorsed by the U.S. Army.

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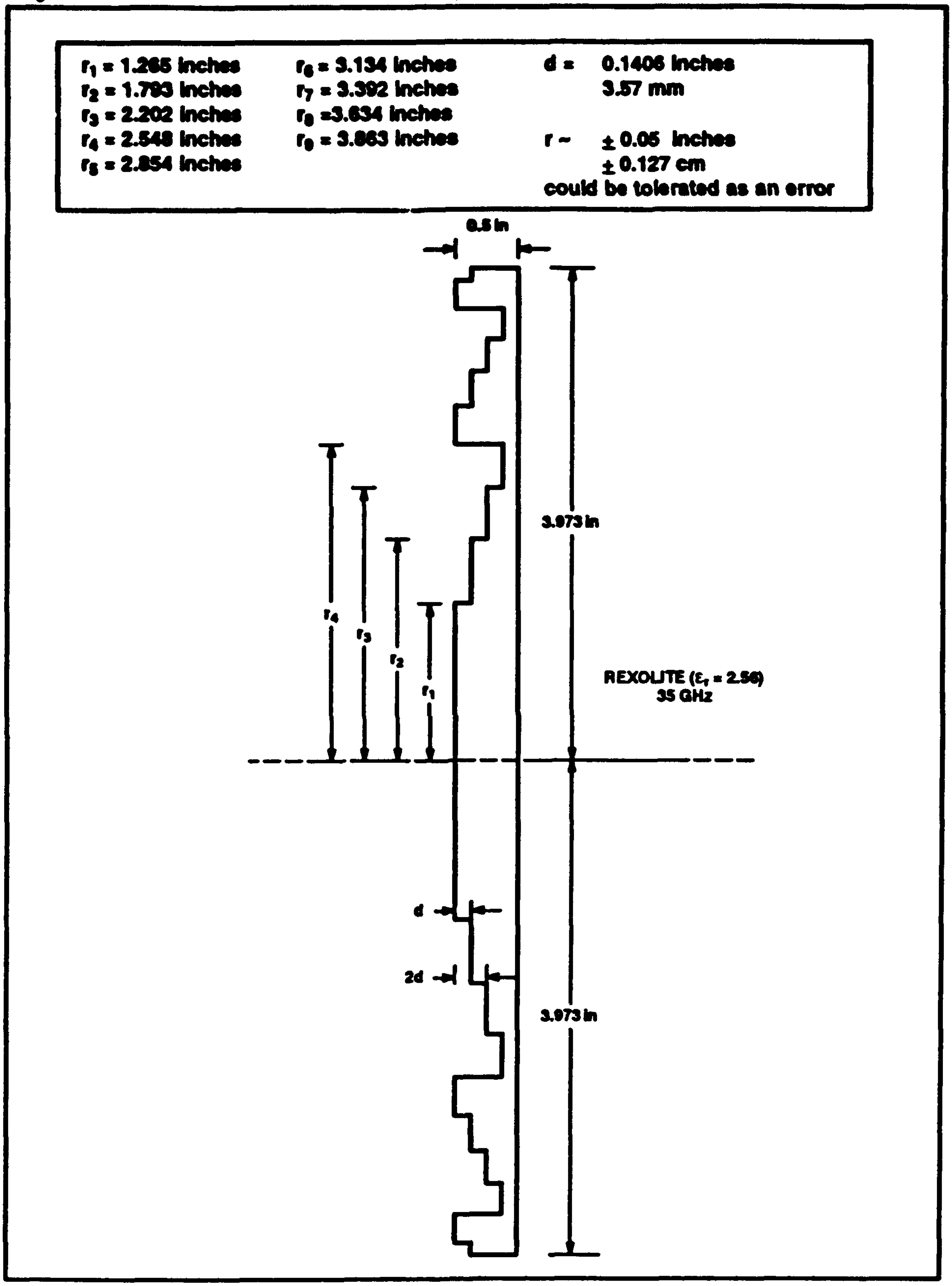
Figure 5. Cross-section of a 35GHz quarter-wave zone plate.



Transmitting Zone Plate

Table I. Examples of Zone Plates at Numerous Millimeter-Wave Frequencies

FREQUENCY	INVESTIGATOR(s)	ZONE PLATE TYPE (PHASE)	DATE
34.6 GHz	Lazarus, Pantoja, Novak & Somekh	Transmission, Partially Opaque	1982
35	Barrett and Wiltse	Transmission; Reflecting Off-Axis ($\lambda/4$)	1992
35	Wiltse	Planar-Dielectric ($\lambda/2$)	1985
36-38	Thornton & Strozyk	Transmission ($\lambda/8$)	1983
54-58	Thornton & Strozyk	Transmission ($\lambda/8$)	1983
90.5	Weibel & Dressel	Transmission ($\lambda/2$)	1967
94	Huder & Menzel	Reflecting ($\lambda/2$)	1988
140	Sobel, Wentworth, Wiltse	Transmission ($\lambda/2$)	1961
210	Sobel, Wentworth, Wiltse	Transmission ($\lambda/2$)	1961
235	Cohn, Wentworth, Sobel, Wiltse	Transmission ($\lambda/2$)	1962

Fig. 6 Pattern of 8in Diameter Transmission Zone Plate (35 GHz)

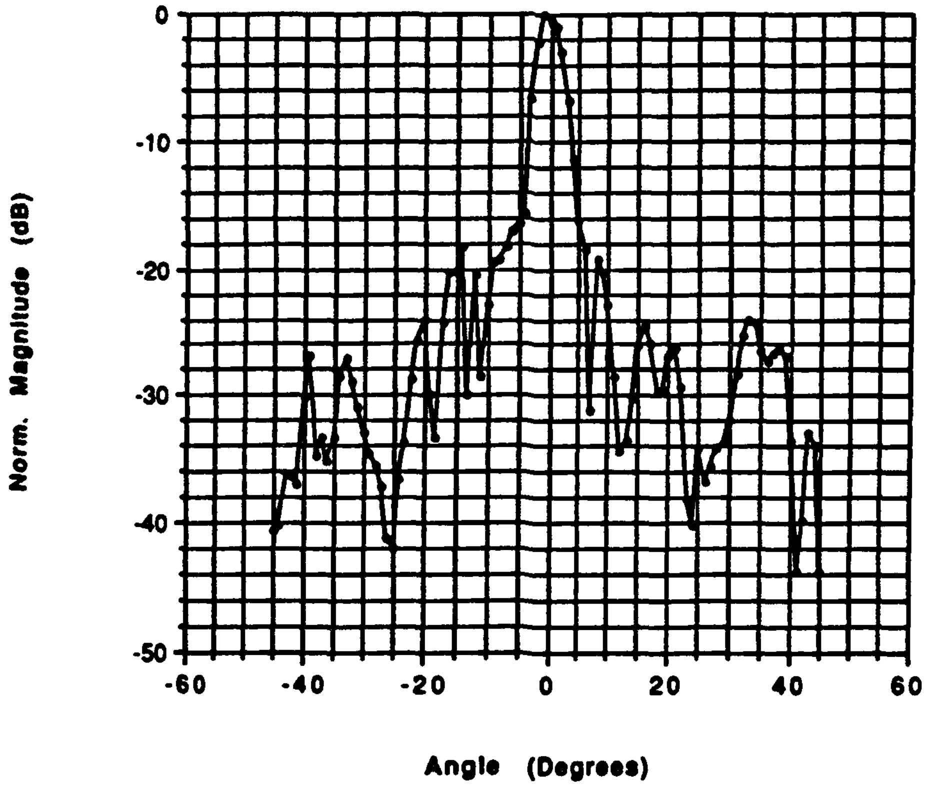
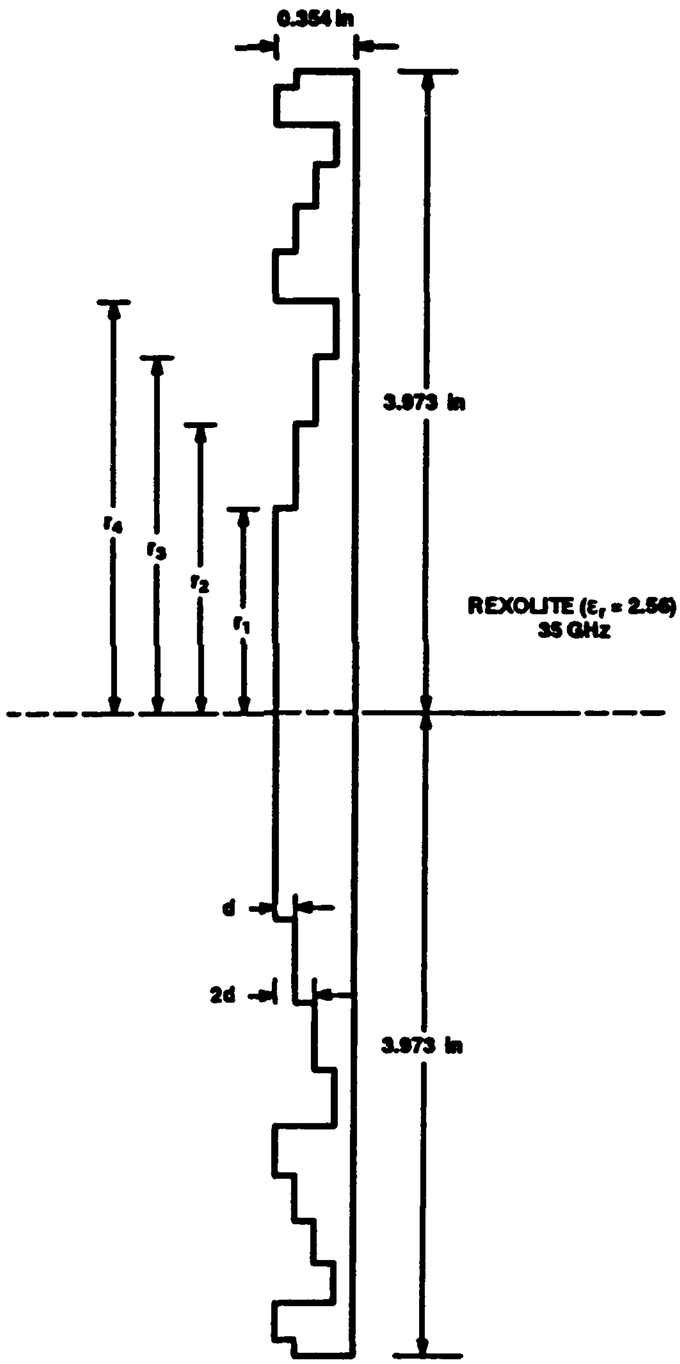


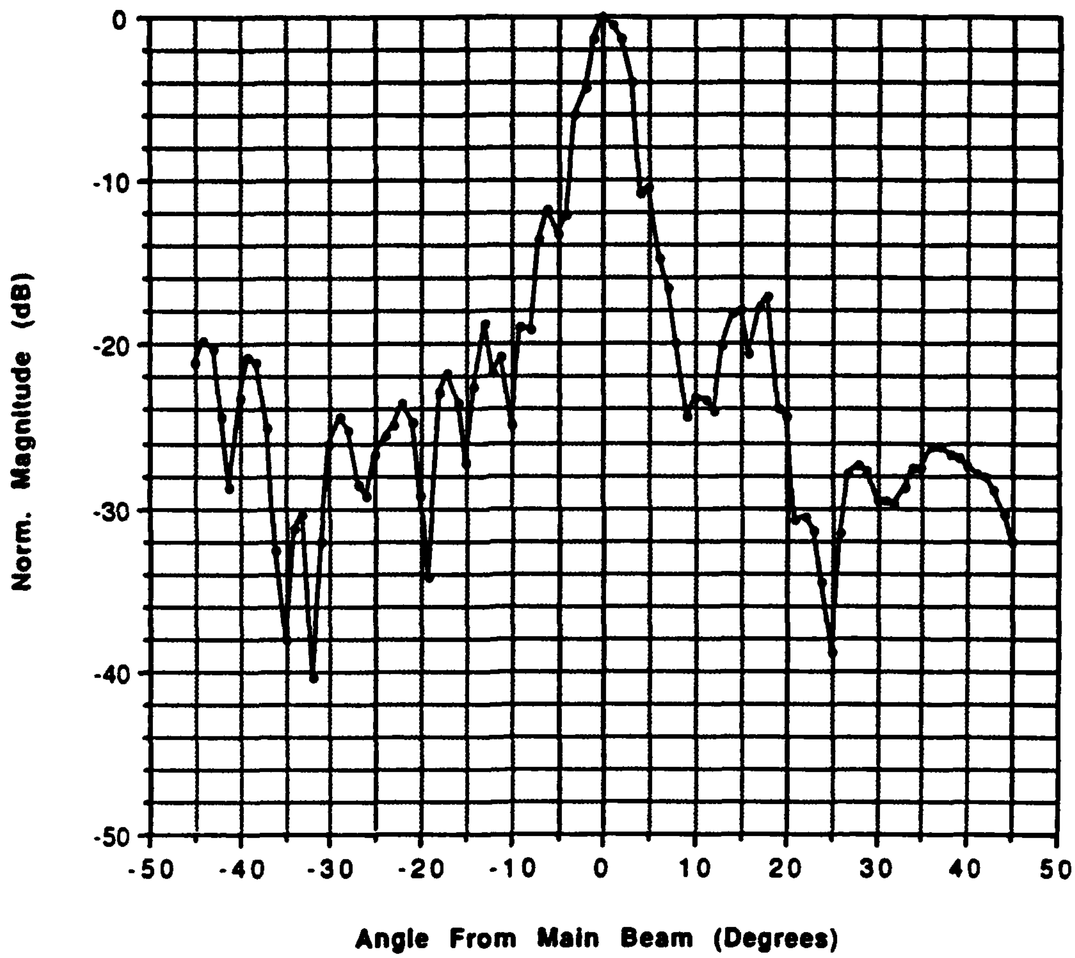
Figure 7. Reflector zone plate for 35GHz (quarter-wave correction).

r_1 = 1.265 inches	r_6 = 3.134 inches	d = 0.0703 inches
r_2 = 1.793 inches	r_7 = 3.392 inches	1.79 mm
r_3 = 2.202 inches	r_8 =3.634 inches	
r_4 = 2.548 inches	r_9 = 3.863 inches	
r_5 = 2.854 inches		



Reflecting Zone Plate

Figure 8. **Pattern of 8in Diameter Reflecting Off-Axis Zone Plate (35 GHz)**



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Off-Axis-Fed Fresnel Zone Plate Antenna

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ABSTRACT

Phase-correcting zone plates may be used with off-axis feeds. For angles up to about 20° off-set, the performance is well-behaved, with minor degradation. The design is given for a transmission type and an equivalent reflecting version having a 17° feed offset. An investigation has been carried out for angles larger than 20°, and the results indicate that the annular zones on the zone plate should not be circular. A ray-tracing analysis shows that the zones need to be egg-shaped, and these results will be described. The analysis has been completed for both transmission or reflection-type zone plates.

GENERAL DISCUSSION

Frequently it is desirable to use an off-axis feed for a zone plate antenna. At other times the off-axis performance is needed in order to consider using multiple antennas or an array of feeds near the focal region. In an earlier article[1] it was shown that for a particular transmission-type, phase-correcting zone plate the performance was good out to angles of about 20°. A later article[2] described an offset-fed reflecting zone plate which used a feed at 30° and zones of elliptical, rather than circular shape. Antenna patterns were given and gain versus frequency results were plotted. These results can be compared with the prior work of Huder and Menzel[3] and others[4], who have used on-axis feeds with reflecting zone plates. In references 2 and 4 an article by Sanyal and Singh[5] was cited in which measured characteristics of the focal region were described. However, it has been found since then that the Sanyal and Singh results were obtained for an incorrectly designed phase-correcting zone plate. Thus the characteristics of the focal-region are not well-known.

Two 35 GHz zone plates of 20 cm diameter have been built and tested. One is an on-axis transmission type and the other is a reflecting type with feed offset by 17°, which is enough to prevent blockage of the antenna beam by the feed. A ray-tracing design for the general offset-fed case has been carried out.[6] The results for angles greater than 20° will be discussed and a specific design will be given for a 35 GHz reflecting zone plate of 20 cm diameter and 30° offset angle.

---

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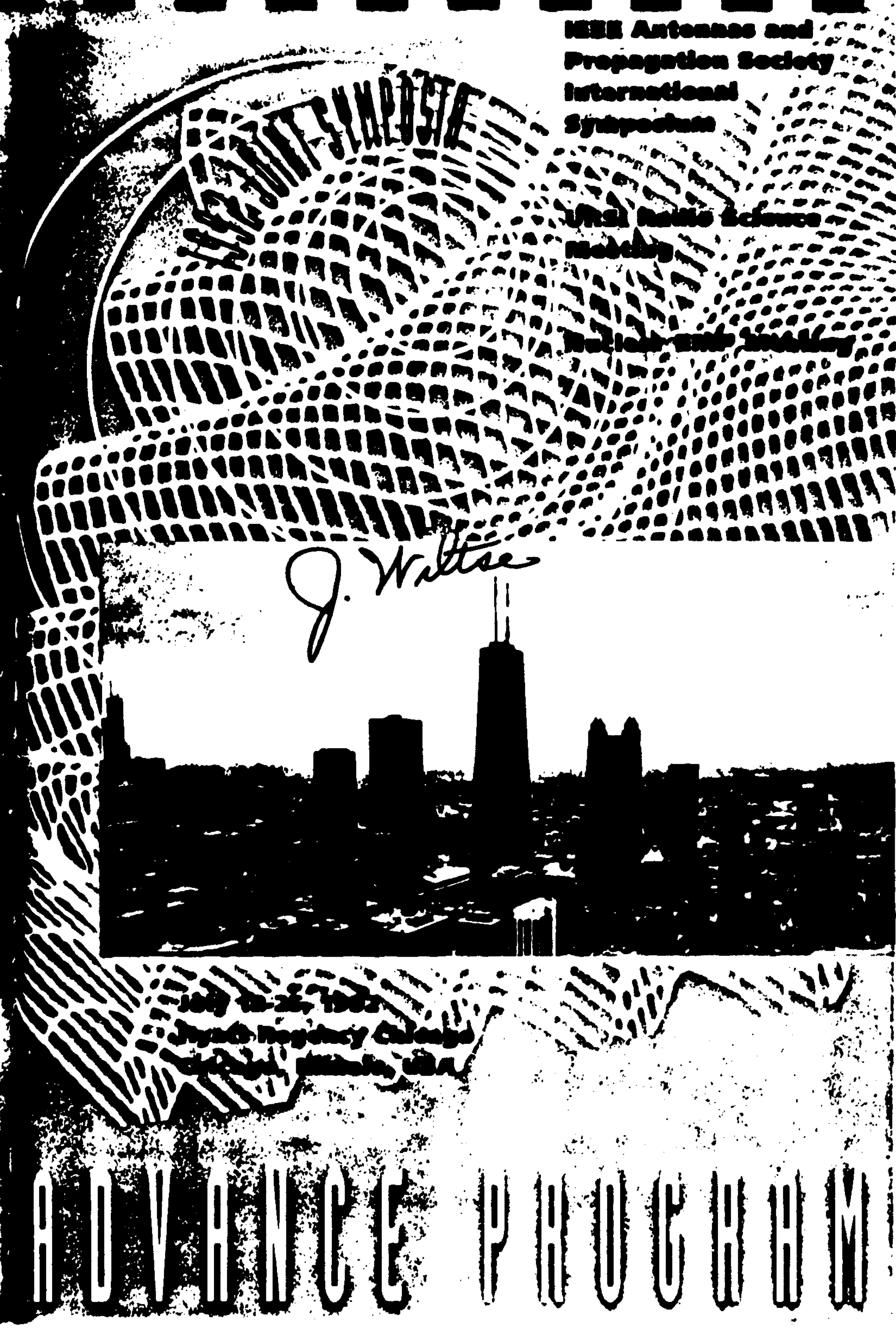
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DESIGN PARAMETERS FOR ZONE PLATE ANTENNAS

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Fresnel zone plate antennas have been proven to be a sufficient replacement for both lenses and parabolic reflectors. This paper only deals with the phase correcting zone plate, and the theory behind this type of zone plate has been covered by Black and Wiltse [1].

The design parameters of the circular Fresnel zone plate are the diameter, focal length, frequency, degree of phase correction, and dielectric material. These quantities may then be used in a set of design equations, previously derived [1], to calculate the dimensions of the zones. The radius of the n^{th} zone is given by:

$$r_n = \sqrt{\frac{2}{P}nF\lambda_o + \left(\frac{n\lambda_o}{P}\right)^2} \tag{1}$$

where F is the focal length and λ_o is the freespace wavelength. P is the phase-deviation factor with P=2 for a phase-reversing zone plate, and P=4 for the quarter-wave plate.

For the phase-correcting plate the groove depth, d, cut into the dielectric to form the zones is:

$$d = \frac{\lambda_o}{P(\sqrt{\epsilon_r}-1)} \tag{2}$$

where ϵ_r is the relative dielectric constant of the zone plate material. For the phase-reversing case there is only one groove depth, but for the quarter-wave correction case there are successive groove depths of zero, d, 2d, and 3d cut in repetitive order.

The error involved with an incorrect depth of cut can be determined using vector analysis. The phase reversing zone plate can be thought of as two partially opaque zone plates in parallel. The first zone plate has alternating transmissive zones with no phase correction. The remaining zones are blocked (i.e., opaque). The second zone plate has alternating transmissive zones that introduce a λ/2 phase correction with opaque zones in between. Note that the second zone plate has transmissive zones where the first zone plate has opaque zones and vice versa.

The resulting vector diagram at the focal point due to the first zone plate spans between 0° and 180° (choosing an arbitrary phase reference). Therefore, the total radiation can be summed into one vector at 90° representing the first zone plate. The second zone plate would have a vector sum at 270° if there were no phase correction; however, with a λ/2 phase correction, the second zone plate has a vector at 90° also. Since the two vectors point in the same direction, they add maximally and produce a high intensity focal point. On the other hand, if an incorrect phase correction is applied (i.e. an incorrect depth of cut), the vector from the second zone plate will not point at 90°. The incorrect phase correction will cause it to point at some other angle and the two vectors will not add maximally resulting in a lower intensity focal point.

This type of error has occurred in a previous investigation [2]. Sanyal and Singh reported no improvement in going from a transmission half-opaque zone plate to a "phase reversing" plate. However, the depth of cut for their X-band example was d = 1.0 cm, but it should have been d=2.67 cm. Instead of adding in phase, their two vector sums were adding at 67.5 degrees, giving a resultant comparable in size to each vector.

The first step in the design of the zone plate is to choose the dielectric. From the above equations, one can see that the radius of the n^{th} zone (and, hence, the diameter, focal length, and number of zones) is unaffected by the choice of dielectric. The depth of each groove, however, is related to the inverse square root of the dielectric constant. Typical choices of dielectric material used are Teflon (ϵ_r = 2.1) and Rexolite (ϵ_r = 2.54). Figure 1 illustrates the correlation of frequency, depth of cut, and dielectric constant.

Frequency, diameter, focal length, and number of zones are all interrelated through the radius equation (1). If the diameter, D, is chosen such that $D = 2r_N$, then for a phase reversing zone plate, equation (1) can be solved for N,

$$N = \frac{2D}{\lambda_o}\left[\sqrt{\left(\frac{F}{D}\right)^2 + \frac{1}{4}} - \left(\frac{F}{D}\right)\right] \quad (3)$$

Figure 2 is a plot of N versus F/D for different diameters. An increase in diameter leads to an increase in the number of zones. Also, for a given diameter, a decrease in F/D (or focal length) results in an increase in the number of zones on the zone plate. A plot of the number of zones versus frequency with F/D = 1, can be seen in Figure 3 for several different diameters. This plot shows that an increase in frequency results in a more dramatic increase in the number of zones for larger diameters.

After the parameters have been determined using the above procedures, equation (1) can be used to find the radius of each zone by substituting 1,2,...,N for n where N is the total number of zones. The depth of cut can also be determined using equation (2).

An experimental design was carried out at 35 GHz for both a transmitting and a reflecting zone plate. For practical reasons (availability of a horn antenna) a design with F/D = 1.2 was chosen. The diameter of the zone plate antenna was limited to some extent by the far field range used to measure the antenna, so D = 20 cm was chosen. These figures resulted in a $\lambda/4$ phase correcting zone plate with 8 full zones and one partial zone. The groove depth, d', for a $\lambda/4$ phase correcting plate was 3.57 mm. The grooves were cut in Rexolite which had been milled to a thickness of 0.61 inches. A reflecting zone plate was also fabricated using the same design parameters. The physical measurements for the reflecting case are the same as for the transmission zone plate, except the depth of cut is half as thick since the incident rays on a reflecting plate travel through the zone plate twice.

The design of the reflecting zone plate is based on the feed being directly in front of the center of the zone plate, but this causes unwanted feed blockage and increases sidelobe levels. Previous work by Garrett and Wiltse [3] has shown that the intensity at the focal point does not significantly diminish for feeds off-axis by up to 20° for the transmission zone plate. If this same idea is applied to a reflecting zone plate, then an angular deviation of the feed from the axis of the zone plate would bring about a corresponding deviation in the reflected beam. Simple trigonometry reveals that moving the focal point by 17° will bring it out of the path of the main beam. This idea was utilized in the setup of the reflecting zone plate. Measurements of these antennas are now underway and will be presented at the symposium.

Recently, there has been a desire to move the feed of a reflecting zone plate to an angle greater than 20°. The design of this type of zone is easier to analyze using the analogous transmissive case as depicted in Figure 4. A ray emanating from the focal point that passes through the center of the zone plate remains unchanged. If a $\lambda/2$ phase correction is desired, the first step is to find the radii that correspond to paths that are a multiple of $\lambda/2$ larger than the focal path. Thus the path corresponding to the radius of the n^{th} zone is $n\lambda/2$ larger than the focal path. At point D on the zone plate the path length on the "focal" side of the zone plate increases by some amount Δx_1, while the path length on the other side of the plate decreases by some amount Δx_2. The radius of the n^{th} zone corresponds to the point where $\Delta x_1 - \Delta x_2 = n\lambda/2$. Using simple trigonometry the expressions for Δx_1 and Δx_2 are

$$\Delta x_1 = -F + \sqrt{F^2 + 2Fr_{nu} \sin\beta + r_{nu}^2} \qquad (4)$$

$$\Delta x_2 = r_{nu} \sin\beta \qquad (5)$$

where β is the angle that the line drawn from the focal point to the center of the zone plate makes with the horizontal as shown in Figure 10, and r_{nu} is the radius of the n^{th} zone on the upper half of the vertical axis of the zone plate. These equations can be combined to form the following:

$$-F + \sqrt{F^2 + 2Fr_{nu} \sin\beta + r_{nu}^2} - r_{nu} \sin\beta = n\frac{\lambda}{2} \qquad (6)$$

A similar equation results for the radius of the n^{th} zone on the lower half of the vertical axis:

$$-F + \sqrt{F^2 - 2Fr_{nl} \sin\beta + r_{nl}^2} + r_{nl} \sin\beta = n\frac{\lambda}{2} \qquad (7)$$

These equations cannot be solved explicitly for the radius of the n^{th} zone; however, there are many equation solving programs that are quite capable of solving these equations for r_{nu} and r_{nl} if F, λ, and β are given.

The radii on the horizontal axis can be solved for using the same analysis as above in the plane containing the horizontal axis of the zone plate and the focal point A. This yields the same results as given in equation (1) with P = 2. The reflecting zone plate would require the same depth of cut as explained in the experimental setup, i.e. depth of cut = ½d, where d is given in equation (2) with P = 2.

A theoretical design was carried out at 35 GHz (λ = 8.57 mm,) with F = 20 cm and β = 30°. The following is a table of the results for the first five zones:

n	r_u (cm)	r_l (cm)	r_h (cm)
1	4.9	4.4	4.2
2	7.3	6.2	5.9
3	9.3	7.4	7.3
4	10.7	8.6	8.5
5	12.3	9.6	9.5

r_u, r_l, and r_h are the radii on the upper half of the vertical axis, the lower half of the vertical axis, and the horizontal axis respectively.

The above data shows that the rings on the lower half of the zone plate are almost circular, while the rings on the upper half of the zone plate are slightly elliptical with an eccentricity of about 1.20. As β decreases, the eccentricity decreases. The resulting zone plate, therefore, is not much different than a zone plate with an on-axis feed and circular rings. This explains the relatively good performance of such a zone plate when its feed is moved off-axis by as much as 20°. If β is larger than 20°, then the elliptical design procedure should be implemented to obtain maximum intensity at the focal point.

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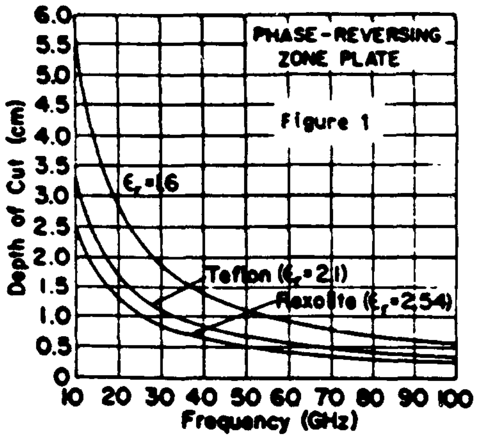

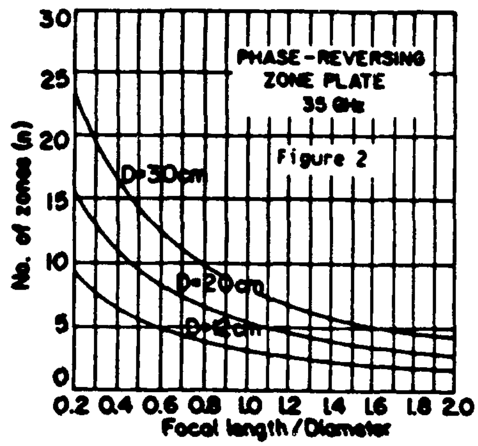

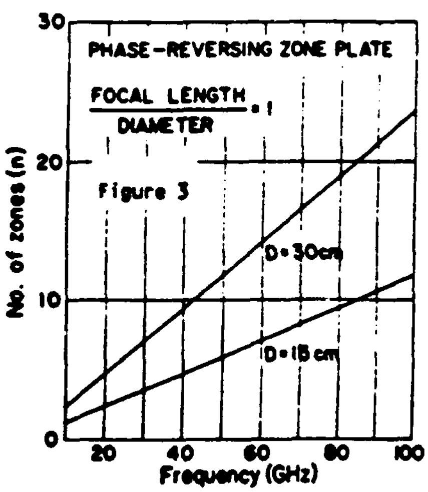

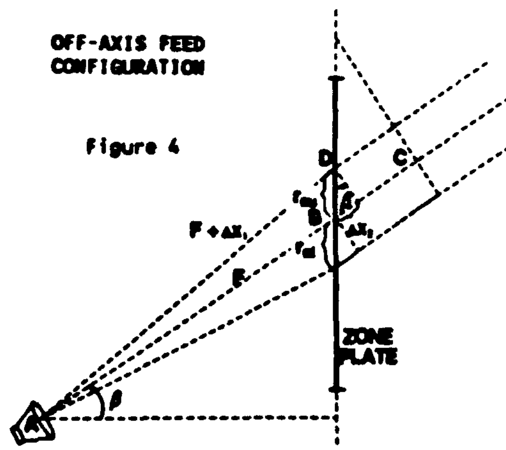

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RECENT DEVELOPMENTS IN FRESNEL ZONE PLATE ANTENNAS AT MILLIMETER WAVELENGTHS

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The Fresnel zone plate antenna has seen further development in the recent past. Analytical results and measured data have been obtained at various frequencies to describe the efficiency, bandwidth, far-field pattern, and focal-region and off-axis behavior. Both transmission (i.e., lens-like) and reflective configurations have been used [1,2]. Horn antennas have typically been used as feeds, but recent measurements at 220 GHz have utilized a dipole (or an array of dipoles) for a feed [3,4]. Off-axis feed methods have recently been developed for reflective zone plates (of elliptical cross-section). This arrangement can produce a better far-field pattern (lower sidelobes), because the feed blockage is reduced.

Very recently work has been reported on the analysis of focal field distributions of zone plate antennas [5]. Experimental measurements are being planned to confirm these distributions. An investigation has also been reported on high-efficiency phase-correcting zone plates [6]. This takes into consideration the optimum feed characteristics.

The presentation will summarize results at several millimeter wave frequencies and indicate areas still being investigated. Quantitative data will be given for the parameters mentioned above. This work was supported in part by the U.S. Army Research Office. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army.

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ERRORS IN SOLUTIONS FOR WAVEGUIDES OF ELLIPTICAL CROSS-SECTION

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In recent years, several papers have been published dealing with enclosed or surface-waveguides of elliptical cross section. Examples have included hollow metal waveguide, enclosed waveguide filled with one or more dielectrics, coaxial transmission lines, dielectric surface waveguides, and waveguides employing anisotropic media. Some of these types have been investigated experimentally, and several have been used in practical microwave-frequency applications, such as in feed lines for antenna installations.

Unfortunately, several of the solutions in the literature contain significant errors. The solutions are extremely complex, involving infinite series of products of radial and angular Mathieu elliptical boundaries. This case is most often treated since non-confocal solutions are even more difficult. Solutions containing errors have been identified and corrections have been suggested. Errors have been found by the authors and others that relate to hollow metal waveguides, coaxial lines, and dielectric rod surface waveguides.

As an example, an article was recently published [1] discussing errors in the field pattern of the TM_{01} mode in a hollow metal waveguide of elliptical cross section. The article referred to the original field representation given by Chu in 1938. [2] However, the proposed corrections have already appeared in the literature. In fact, the error in the TM_{01} field configuration was first mentioned by Krank in 1962. [3] Two years later, Piefke gave a plot of the correct field pattern. [4] In 1971, Kretzschmar published an article [5] giving a theoretical argument and practical measurements confirming Piefke's plot.

Since its publication, several other authors have discussed errors in the original Chu paper. These include limitations in the validity of his solutions due to the use of asymptotic expansions for the modified Mathieu functions, and the resulting errors in his formulas for attenuation and surface impedance. Kretzschmar addressed the topic first [6], using a different method to obtain curves that were quite different from those obtained by Chu. This work was discussed further by Falciasecca, et al. [7] The following year, Lewin and Al-Hariri [8] pointed out additional limitations in these solutions, and proposed a correction to the attenuation formulas. However, Rengarajan and Lewis have shown that their results are also limited. [9] Reference 9 contains a summary of these conclusions.

Errors in other papers will be addressed in the presentation. The investigation involved an extensive literature search, and a detailed and lengthy bibliography is available. In addition, abstracts of most of the articles have been prepared. The identification of the errors encountered in the prior literature and possible steps to correct these errors should be of significant use to workers in the field. The results constitute a collection of material defining the state of analysis and measurement in this field, and should be of importance to future research.

This work was supported in part by the U.S. Army Research Office. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army.

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Further Comments on "Modes of Elliptical Waveguides: A Correction"

J. C. Wiltse and T. H. Gfroerer

In the above paper[1], the authors discuss the TM_{01} mode in elliptical waveguides and describe an error in the field configurations plotted in the early article by Chu [1] and repeated in the book by Marcuvitz [2]. The authors comment "that the error had apparently gone undetected for some five decades." This is not correct, and in fact, this and other errors in the Chu article have been discussed by numerous authors over a period of many years.

The specific error dealing with the TM_{01} mode was first pointed out by W. Krank in 1962 [3]. In 1964 Piefke [4] published a detailed analysis of the modes and gave plots of the correct field configurations (see Fig. 3(g), p. 261, for the TM_{01} mode). Kretzschmar also published several articles (two in these transactions) on the subject in 1970 [5], 1971 [6], and 1972 [7]. In particular, in the 1971 article he specifically pointed out the Chu error for the TM_{01} mode fields and showed plots of Chu's configuration and the correct version. The arguments given by Goldberg *et al.* for the corrected field configuration are similar to Kretzschmar's discussion [6].

In the paper by Goldberg *et al.* they state (p. 1605, Section III): . . . "the exact solutions (method 1) clearly lie off Chu's curves for the higher eccentricity. This would suggest that the accuracy of either the tables or the truncated expansions used by Chu decrease in the limit of large q and small ξ." Lewin and Al-Hariri published a paper in 1974 which already demonstrated that the expansion used by Chu is not valid unless ξ is large. In fact, Chu himself concedes the assumption of large ξ (p. 588, top right column). Also included in Lewin and Al-Hariri's paper is a correction of the error.

Over the years, several other authors have discussed various errors in the original Chu paper. These include limitations in his results because of his choice of particular asymptotic formulas for the radial Mathieu functions, and errors in his solutions for attenuation and surface impedance [8]–[11]. Reference [11] contains a compilation of previous conclusions. In summary, the results given by Goldberg *et al.*, have already been described in the literature, and in addition, the earlier papers contain more information about mode configurations and propagation characteristics.

This work was supported in part by the U.S. Army Research Office. Opinions, interpreta'ions, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army.

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Authors' Reply[2]

David A. Goldberg, L. Jackson Laslett, and Robert A. Rimmer

This letter is in reply to the comments of Dr. J. B. Davies and of Drs. J. C. Wiltse and T. H. Gfroerer on our paper. Despite our modest intentions, our paper seems to have created something of a tempest in an (elliptical) teapot. We deeply regret this.

Addressing the comments of Dr. Davies first, we would like to thank him for calling attention to several articles dealing with the modes of elliptical waveguides which we had omitted from our bibliography. Another work which we have become aware of since the publication of our article (which is also included in the Wiltse and Gfroerer bibliography) is

> B. Rembold, "Elliptische hohlleiter, tafeln für die Grenzwellenlängen und Dämpfungskonstanten," *Archiv für Electronik and Übertragungstechnik*, vol. 29, pp. 449–453, Nov. 1975.

Our failure to be fully conversant with the relevant literature is at least partly due to the fact, evident from our biographies, that none of the authors is a regular practitioner in the microwave field.

Having said that, we feel obliged to point out that the main point that we wished to make in our paper, was *not* any disagreement

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with Chu's eigenvalues (which as we noted proved remarkably accurate for the case of $e = 0.75$), but rather that the correct field pattern for the TM_{01} mode was *qualitatively* radically different from Chu's; neither Rembold's paper, nor any of those referred to by Dr. Davies, addresses the question of the field shape of the TM_{01} mode. We should also note that, having found Chu's figure reproduced in the 1986 reprinting of Marcuvitz's book (which, we are informed by colleagues, is something of a "bible" in the field), with no mention of any associated erratum, we restricted our literature search to papers published after 1985, and, in any case, to papers showing the actual field shapes (we found none). Although it was not the purpose of our note to present a comprehensive study of the elliptical waveguide, we nonetheless welcome Dr. Davies' suggestions for remedying the noted deficiencies in our bibliography.

Finally a note on the "demystifying" of Mathieu functions. It has been our experience that not all of our colleagues are as conversant with these functions as Dr. Davies obviously is, and our remark was intended as a somewhat light-handed way of acknowledging this fact. We regret any offense that may have been given; none was intended.

Many of the above remarks are equally applicable to the comments of Wiltse and Gfroerer. In particular, [11] in their article, which is said to summarize the various corrections to the Chu paper, refers exclusively to wave-impedance calculations and makes no reference whatsoever to field shapes.

The work described in [6] in their article (the 1971 Kretzschmar paper) is another matter. As we stated in replying to Dr. Davies's comments, we relied on what a number of electrical engineering colleagues advised us was the standard reference work (Marcuvitz's *Waveguide Handbook*,) and only searched the *subsequent* literature, so we were indeed ignorant of Kretszchmar's work on the error in the field shapes. While it does not fully exonerate us, we find our ignorance of this subsequent work places us in rather learned company: In addition to the three referees of our paper, we would add Dr. Julius Stratton (Chu's thesis advisor), Dr. N. Marcuvitz, and, apparently, Kretzschmar's co-author on a 1972 paper on elliptical waveguides, one J. B. Davies. (Whether we should be similarly faulted for our ignorance of an unpublished 1962 thesis from the Aachen Technische Hochschule, we leave to the judgment of your readers.)

Part of the difficulty seems to be the lack of "standard references" which are up to date; despite the apparent "textbook" nature of the elliptical waveguide problem, none of the sources for the corrections referred to by either Davies or Wiltse and Gfroerer is such a source. In fact one of our main motivations in writing the paper was to point out a qualitative error that had persisted in the latest edition of one of the most heavily relied on standard sources. Indeed, our decision to publish in IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, rather than the *Journal of Applied Physics* (in which Chu's paper originally appeared), was to bring the correction to the attention of the widest possible audience. We feel fairly certain that the combination of our article and the lively correspondence it has generated will achieve that goal, if not precisely in the way originally intended.

In closing, we would like to thank the authors of the two letters for their interest and comments, and, since we have not yet explicitly done so, to extend our apologies to Dr. Kretzschmar for inadvertently taking the credit which is rightfully his.